Use of a GIS-interpolation method (ANOVA) for modelling and mapping soil-water erosion processes in Lebanon

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1. Abstract

Soil erosion by water represents a serious threat to the natural and human environment in Mediterranean countries, including Lebanon which represents a good case study. This research proposes a conditional decision-rule interpolation based model to predict the distribution of multiple erosion processes (i.e., sheet, mass and linear) in a representative area of Lebanon from the measured erosion signs in the field (root exposure, earth pillars, soil etching and drift, and linear channels). First, erosion proxies were derived from the structural OASIS classification of Landsat TM imageries combined with the addition of several factorial erosion maps (e.g, slope, drainage) under a GIS environment. Secondly, erosion signs were measured in the field, and interpolated by the statistical *moments* (means and variance – ANOVA model) in the defined erosion proxies, thus producing quantitative erosion maps (tons/ha) at a scale of 1:100000. Seven decision rules were then generated and applied on these maps in order to produce the overall decisive erosion map reflecting all existing erosion processes, i.e. equality, dominance, bimodality, masking, aggravating, dependence and independence.

The produced erosion maps are ranging between 0 and more than 1.8 tons/ha for sheet erosion, and 0 and more than 10.5 tons/ha for mass and linear erosion. They are fairly matching with coincidences values equal to 43% (sheet/linear), 48% (sheet/mass) and 49% (linear/mass). The overall accuracies of these maps were estimated to be 76% (sheet erosion), 78% (mass erosion) and 78.5% (linear erosion). The overall decisive erosion map with fifteen classes corresponds well to land management needs. The model used is relatively simple, and may also be applied to other areas. It is particularly useful when GIS database on factors influencing erosion is limited.

2. Introduction

Soil erosion by water is a serious geo-environmental problem in the Mediterranean region causing both on- and offsite effects. The implementation of effective soil conservation measures has to be preceded by a spatially distributed assessment of diverse erosion processes (i.e. sheet, linear and mass erosion), each process requiring different priority interventions; and mixed erosion processes affecting the same areas have to be determined in the evaluation of land management scenarios.

This erosion assessment was commonly performed using several physically based soil erosion models (e.g. Morgan and Quinton, 2001; Kirkby et al., 2002; Hessel and Jetten, 2007); however, the application of these models is inhibited in some countries like Lebanon due to their complexity, and their need of huge amount of input spatial data is difficult to acquire. In this context, this study focuses on building a simple, realistic, informative and practical decision-rule-based conditional model to predict the geographic distribution of sheet, linear and mass erosion processes in Lebanon and evaluate its accuracy. The proposed model is based on the measurement and spatial interpolation of visible erosion signs collected on the defined erosion proxies, whose internal characteristics influence the occurrence of soil erosion, and whose spatial content enables their capture and modelling by remote sensing and geographic information systems (GIS). Thus, sheet erosion, the initial phase of the erosive process, leading to the removal of most of the surface horizon, was recognized by the presence of exposed tree roots under forests, and earth pillars in agricultural fields and bare lands. Linear erosion appears when sheet runoff becomes more organized, digging deeper and deeper in the ground. The resulting signs are described as channels with different deepness values (i.e. grooves, rills and gullies). Mass erosion as a relatively slow sliding of the surface layers of the soil cover is widely observed on steep slopes where young forest saplings are bent and the base of adult trees crooked. The resulting quantitative erosion maps (tons/ha) at 1:100 000 cartographic scale are converted to a predictive overall erosion map reflecting multiple erosion processes. The latter seems useful for land-use sustainable management and environmental decision-making, adapting the erosion control as closely as possible to the dominant erosion occurring process/es.

3. Methods

The mapping of diverse soil erosion processes (sheet, linear and mass) can be realized in several steps. Satellite imageries (Landsat TM – 30 m) are used to produce the erosion proxies' map defining their boundaries. The latter is combined with some thematic erosion factorial maps (i.e., slope gradient, aspect and curvature, drainage density, vegetation cover density, soil infiltration and movement, and rock infiltration and movement) for specifying erosion proxy properties, and with field surveys as well as aerial photographs for allocating visible erosion signs.

The measured erosion signs at field sites have been interpolated under a GIS environment using a statistical classification ANOVA model that assumes that erosion variation within a given proxy is smaller than that between proxies, specifically at the considered working scale (1:100,000). This interpolation model considers that spatial erosion change takes place at proxy boundaries which are sharp and not gradual. It is based on mean and variance of the erosion measured volumes (tons/ha) at the locations within those proxies (Burrough and McDonnell, 1998):

$$z(x_0) = \mu + \alpha_k$$

Where z is the value of the erosion volume at location x_0, μ is the general mean of z over the erosion proxy, and α_k is the deviation between μ and the mean of class K. This method of interpolation is commonly used in soil pollution mapping (e.g. Bruland et al., 2006) and recognized as reliable for global prediction (Schloeder et al., 2001).

The obtained raster interpolated erosion maps (sheet, linear and mass) by applying this statistical model are then reclassified into seven classes each for better visualization, easier interpretation and further comparison. The used classification method refers to standard deviation with a certain merit in that it uses the mean to generate class breaks and allows dividing each map into classes by adding or subtracting one standard deviation at a time. This allows adjusting objectively the class boundaries refining suitable erosion processes as follows: 1) one class is characterizing non-eroded areas (soil loss equal 0), another one is dedicated to dense urban areas suffering from off-sites effects of erosion, and the five other classes reflecting soil loss in tons/ha.

A conditional rule-based model is then explored on the resulting attribute table of the intersected erosion maps to produce a map showing dominant erosion process in a given area or associated ones for priority interventions. The model used is practical, easy to understand, and has the ability to analyze a large set of data records with three different variables (i.e. sheet, linear and mass erosion). It comprises seven decision rules, i.e equality (ER), dominance (DOR), bimodality (BR), masking (MR), aggravating (AR), dependence (DER) and independence (IR), generated specifically for characterization of real non-ordered erosion combination processes prevailing in the study area (64 real cases of a total of 216 possible cases) **(Table 1)**. For example, the dependence rule (DER) was closely related to soil depth, which is necessary for determining critical tolerance values for erosion (Whiting et al., 2001). Thus, a shallow soil (depth < 1 m) can be considered as higher erosion risk area than deep one (depth > 1 m). DER affects the biggest number of erosion combination real cases, highlighting the effect of soil depth in conditioning erosion occurrence.

Equality (ER) and aggravating (AR) decision rules can have similar appearance frequency in a given area (i.e. erosion combination cases), but they can affect unequal areas. This indicates that erosion processes tend to increase or decrease proportionally in a parallel trend (ER) within a given proxy, while high or very high erosion values for one or two processes (AR) is due mainly to extreme erodibility of terrains, or anthropic interference (quarrying, building excavation or road construction) aggravating their susceptibility to erosion.

DOR is more frequently appearing than BR and MR that have equal distribution. Thus, a given erosion process can be dominant in some localities, with the absence of other erosion processes (DOR); or two erosion processes can have the same occurrence level and the third one is not manifested (BR); or two erosion processes can be high/very high in few cases and the third one is attributed to the low class (MR).

Using the seven decision rules, the corresponding intersected map of erosion processes is converted under a GIS environment into a predictive overall erosion map, specifying for each proxy the existing erosion processes. This map can be used for decision-making of the remedial anti-erosive measures that have to be applied and which are different according to the erosion process.

4. Results

4.1. Soil-water erosion processes' maps

In the produced sheet erosion map with seven classes, class 3 [low erosion; soil loss (SL) varying between 0.225 and 0.6 tons/ha] and class 4 (medium erosion; 0.6 < SL < 1.125 tons/ha) cover the largest area (45%). Class 6 (very high erosion) with soil loss exceeding 1.8 tons/ha often corresponds to sandy soils of Mount Lebanon (22.5%). The high (class 5) to very high (class 6) mass erosion characterize a large part of the studied region (33%; SL between 6 and more than 10.5 tons/ha), whereas 27% of the region is covered by the very low (class 2) to low (class 3) mass erosion (0 < SL < 1.5 tons/ha). This indicates a widespread of terrain degradation by mass erosion due to torrential rainfall and high occurrence of morpho-tectonic events (uplift, faulting, jointing and earthquakes). In the produced linear erosion map, classes 2 and 3 (0.15 < SL < 4.5 tons/ha) have nearly close areas (30%) than classes 4 and 5 (7.5 < SL < more than 9.75 tons/ha). The two maps of mass and linear erosion are more dependent on time than sheet erosion map, because the occurrence of the former processes may change drastically due to human activities.

4.2. Comparison of erosion processes' maps

The comparison between erosion maps reveals a poor agreement between erosion processes. Only 43% of linear erosion classes coincide with sheet eroded ones **(Table 2a)**. Similarly, matching between mass erosion and sheet erosion on one side, and linear erosion from the other side is equal to 48% (M-S) and 49% (M-L), respectively **(Tables 2b & 2c)**. However, if we take into consideration the six erosion classes separately, the degree of coincidence can increase in some cases. But this degree differs significantly between the producer of the map and its user. Areas without erosion (class 1) are showing very high coincidence either for the producer or the user, varying between 81 and 91% depending on the erosion process.

This good accord is due to the effective protection of considered areas against erosion (maintained terraces, embankments, etc.), or their geomorphologic characteristics without any ability for triggering erosion, or the absence of soil cover as a consequence of past erosion. Very high eroded classes (no. 6) are revealing also a better agreement than intermediate classes (no. 2, 3, 4 and 5), showing inverse reasons than those mentioned previously. This agreement oscillates between 56 and 66% for the user; and 46 and 71% for the producer. It indicates quasi-similar values once sheet and gully erosion maps are compared for both user and producer reflecting a close relation between these two processes if they are extremely high. For mass erosion, a higher coincidence of very high classes (no. 6) is noticed for the producer once sheet erosion is considered (71%); while a higher one is related to the user if gully erosion is compared (66%). Thus, the relation between sheet and gully erosion processes is more convenient than that between sheet/mass erosion or between gully/mass erosion.

The conditional model based on decision rules applied on the intersected erosion processes' maps produces an overall erosion map with multiple processes and total accuracy of 77%. In this map, fifteen classes were distinguished showing the combined three erosion processes with various classes (i.e. SML – 1, 2, 3, 4, 5 and 6), two erosion processes (ML – 2, 5, 6, 2SL and 2SM), and one erosion process (2L, 2M, 2S and 3S). Class 4SML (medium erosion) covers the largest part of the study area (21%), highlighting the high occurrence of multiple equivalent erosion processes degrees in most proxies with considerable soil loss. This class has also the largest number of polygons (57 of a total of 363) indicating a highly dispersed distribution. Classes integrating three erosion processes (SML) are more dominating in terms of covered area and polygons than those combining two processes (ML, SL, SM), which in turn are governing single processes (S, M, L). This is indicative of the close relation between erosion processes. For example, gully erosion can influence the initiation of mass erosion, and maintained terraces can reduce both sheet erosion and mass erosion over steep slopes. The mixed two erosion processes are sparsely distributed in the coastal plain, Mount Lebanon and Bekaa valley. 2L falls only in the Bekaa plain, combined in some localities with 2S, while 3S is shown in the upper left of the coastal plain.

The generated decision-rules (i.e. equality, dominance, bimodality, masking, aggravating, dependence and independence) are fitting real erosion combination processes prevailing in the study area; however other rules can be created if other areas are considered with the existence of different combination processes. This is an important future research topic since the importance of such rules in explaining additional variance in erosion occurrence can be tested.

5. References

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Table 1 Signification of decision rules used for mapping overall erosion.

Decision erosion rule	Applied equation	
	Input data	**Output result**
Equality	sheet = mass = linear = same erosion class	*OE belongs to that class*
Dominance	2EP = null and 3rd EP > null	*OE = 3rd EP*
Bimodality	2EP = same erosion class and 3rd EP = null	*OE belongs to that class ≠ null, and shares two EP*
Masking	2EP = high/very high erosion class and 3rd EP = low/very low	*OE shares the 2EP belonging to high or very high occurrence degree, thus masking the low or very low erosion levels*
Aggravating	2EP = very high/high erosion class and 3rd EP = high/very high *(respect the order of classes)*	*OE belongs to the very high erosion class*
	2EP = high erosion class and 3rd EP = medium	*OE belongs to the high erosion class*
Dependence	2EP = very low/low erosion class and 3rd EP = medium	• *if SD < 1 m ⇨ OE = medium* • *if SD > 1 m ⇨ OE = low*
	2EP = high/very high erosion class and 3rd EP = medium	• *if SD < 1 m ⇨ OE = very high* • *if SD > 1 m ⇨ OE = medium*
	2EP = medium erosion class and 3rd EP = very high	• *if SD < 1 m ⇨ OE= high* • *if SD > 1 m ⇨ OE = medium*
	1st EP = low/very low erosion class, 2nd EP = medium and 3rd EP = high/very high	• *if SD < 1 m ⇨ OE = high* • *if SD > 1 m ⇨ OE = medium*
Independence	2EP = medium erosion class and 3rd EP = low/very low	*if SD < 1 m or > 1 m ⇨ OE = medium*
	2EP = very high erosion class and 3rd EP = medium	*if SD < 1 m or > 1 m ⇨ OE= very high*

Erosion processes = EP; Overall erosion = OE; Soil depth = SD.

Table 2 Comparison (in km²) between erosion processes' maps.

a) Sheet (S) / Linear (L) erosion

Sheet erosion classes (km^2)	Linear erosion classes (km^2) 1	2	3	4	5	6	Total	*Cp (%)*
1 (nil)	139.5	17.5	0	0	0	0	157	***89***
2 (very low)	25	23	36	9	0	0	93	***25***
3 (low)	4	11	33	119	37	10	214	***15***
4 (medium)	0	34	50	88	36	6	214	***41***
5 (high)	0	0	0	8.5	36	35	79.5	***45***
6 (very high)	0	0	0	6	60	68.5	134.5	***51***
Total	168.5	85.5	119	221.5	169	119.5	**892**	
Cu (%)	***83***	***27***	***28***	***40***	***21***	***57***	***Co = 43%***	

b) Sheet (S) / Mass (M) erosion

Sheet erosion classes (km^2)	Mass erosion classes (km^2) 1	2	3	4	5	6	Total	*Cp (%)*
1 (nil)	144	14	0	0	0	0	158	***91***
2 (very low)	30	16	22	24	0	0	92	***17***
3 (low)	4	32	47	65	46	19	213	***22***
4 (medium)	0	24	45	91	35	20	215	***42***
5 (high)	0	0	0	7	37	35	79	***47***
6 (very high)	0	0	0	11	28	96	135	***71***
Total	178	86	114	198	146	170	**892**	
Cu (%)	***81***	***19***	***41***	***46***	***25***	***56***	***Co = 48%***	

c) Mass (M) / Linear (L) erosion

Mass erosion classes (km^2)	Linear erosion classes (km^2) 1	2	3	4	5	6	Total	*Cp (%)*
1 (nil)	149	30	0	0	0	0	179	***83***
2 (very low)	21	12	12	41	0	0	86	***14***
3 (low)	0	6	60	47	0	0	113	***53***
4 (medium)	0	38	44	71	33	12	198	***36***
5 (high)	0	0	0	48	69	29	146	***47***
6 (very high)	0	0	2	22	67	79	170	***46***
Total	170	86	118	229	169	120	**892**	
Cu (%)	***88***	***14***	***51***	***31***	***41***	***66***	***Co = 49%***	

Cu = User's degree of coincidence; Cp = Producer's degree of coincidence; Co = Overall coincidence.